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Grassland-type ecosystem stability in China differs under the influence of drought and wet events

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Abstract: Ecological stability is a core issue in ecological research and holds significant implications for humanity. The increased frequency and intensity of drought and wet climate events resulting from climate change pose a major threat to global ecological stability. Variations in stability among different ecosystems have been confirmed, but it remains unclear whether there are differences in stability within the same terrestrial vegetation ecosystem under the influence of climate events in different directions and intensities. China's grassland ecosystem includes most grassland types and is a good choice for studying this issue. This study used the Standardized Precipitation Evapotranspiration Index-12 (SPEI-12) to identify the directions and intensities of different types of climate events, and based on Normalized Difference Vegetation Index (NDVI), calculated the resistance and resilience of different grassland types for 30 consecutive years from 1990 to 2019 (resistance and resilience are important indicators to measure stability). Based on a traditional regression model, standardized methods were integrated to analyze the impacts of the intensity and duration of drought and wet events on vegetation stability. The results showed that meadow steppe exhibited the highest stability, while alpine steppe and desert steppe had the lowest overall stability. The stability of typical steppe, alpine meadow, temperate meadow was at an intermediate level. Regarding the impact of the duration and intensity of climate events on vegetation ecosystem stability for the same grassland type, the resilience of desert steppe during drought was mainly affected by the duration. In contrast, the impact of intensity was not significant. However, alpine steppe was mainly affected by intensity in wet environments, and duration had no significant impact. Our conclusions can provide decision support for the future grassland ecosystem governance.

Keywords: grassland ecosystem; stability; resistance; resilience; different climate types; drought climate event; wet climate event

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1 Introduction

Currently, global warming resulting from climate change has led to an increasing frequency and intensity of drought and wet events (Easterling et al., 2000; King et al., 2015; Stott, 2016), significantly impacting terrestrial ecosystem stability (Hansen et al., 2019; Fan et al., 2021; Xu and di Vittorio, 2021; Creedy et al., 2022). An ecosystem's stability refers to the ability of an ecosystem to maintain or restore its own structure and function to maintain relative stability, usually described as resistance and resilience (Hu et al., 2022). Resistance refers to the ability of vegetation to maintain its original productivity level when an ecosystem experiences climate

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events (Li et al., 2020a), and resilience refers to the rate at which the ecosystem recovers to normal productivity after experiencing climate events (Liu et al., 2021). Highly resistant and resilient ecosystems are more stable, and more stable ecosystems have lower variability and stronger buffering capacity when exposed to climate events (Ives and Carpenter, 2007; Chen et al., 2021). Understanding terrestrial ecosystem stability upon exposure to climate event disturbances can provide a scientific reference for ecological barrier protection, management, and services.

The existing research literature showed that terrestrial ecosystem stability varies among different vegetation communities and ecological regions. For example, gymnosperms and angiosperms exhibit different drought resistance and spatial patterns toward drought resistance (Li et al., 2020b). According to de Keersmaecker et al. (2015), semi-arid locations have limited drought resilience, and high latitudes have weak resistance to negative temperature anomalies. van Ruijven and Berendse (2010) confirmed that different vegetation communities have variable resistance and resilience upon exposure to drought conditions by studying the reactions of experimental vegetation communities to different varieties of natural droughts. However, a majority of the currently conducted research focuses on forest ecosystems (Li et al., 2020b). Focusing on the response of forest ecosystems to drought climate, other climate conditions are ignored. Wet climate conditions also affect vegetation, according to Isbell et al. (2015) and Hossain et al. (2022); if the wet event is too severe, the vegetation may undergo irreversible changes (Jiao et al., 2022). For example, Hossain et al. (2022) confirmed that after being affected by a wet climate, cold grasslands and wet temperate ecosystems typically have higher resistance to wet events but lower resilience. However, little research has been conducted on ecosystem stability in wet environments. Therefore, the resistance and resilience of vegetation in wet environments require attention.

In a grassland ecosystem, Liu et al. (2021) computed the whole system stability in response to dry environment, but they did not further analyze the stability variations of various grassland types in the grassland ecosystem. Although Huang et al. (2021) confirmed that there are differences in the stabilities of different grassland types in drought environments, they did not explore how grassland ecosystems react in wet climate. Additionally, it is questionable if grassland ecosystems can remain stable during climate events of varying intensities. Therefore, it is crucial to thoroughly comprehend how well different grassland types survive and recover after harsh climatic impacts resulting from various intensities (mild to moderate or severe level) and orientations (drought or wet).

The grassland ecosystem in China covers almost all grassland types including meadow steppe, typical steppe, desert steppe, alpine steppe, temperate meadow, and alpine meadow (Yuan et al., 2004). In China, the distribution range of different grassland ecosystems spans a large latitude and longitude. The geographical environment also differs, so it is a perfect research subject for addressing the variation in ecosystem stability among different types of grasslands. In this study, we used Standardized Precipitation Evapotranspiration Index-12 (SPEI-12) annual average data to identify the climate events of each year in different orientations and intensities from 1990 to 2019. Then, we utilized Normalized Difference Vegetation Index (NDVI) data to characterize grassland vegetation health status and calculate the resistance and resilience of six different grassland types in China. Most previous studies only focused on quantifying vegetation stability, with little discussion on the intensity and duration of climate events. On this basis, the impact of climate event intensity and duration on grassland ecosystem stability was explored in this study. The novelty of this article includes: (1) further subdividing different grassland types in grassland ecosystem and considering differences in grassland vegetation stability upon exposure to climate environments at different orientations (drought or wet) and intensities (mild to moderate, or severe level); and (2) integrating standardization to provide the explanatory contribution rate of climate event (duration and intensity) on stability based on a traditional regression model method.

This study aimed to identify the stability differences between six grassland types in China, namely meadow steppe, typical steppe, desert steppe, alpine steppe, temperate meadow, and

alpine meadow, under the influence of drought and wet climate events from 1990 to 2019. It also explored the differences in the impact of the intensity and duration of drought and wet events on grassland ecosystems and provided suggestions and decisions for grassland management and protection. In order to achieve the above goals, the three research objectives in this article are: (1) identifying the years and durations of drought and wet climate events for each grassland type in China from 1990 to 2019; (2) calculating the resistance and resilience of different grassland types over the past 30 a and analyzing their stability differences under climate event environments in different intensities and orientations; and (3) for the grassland types with the worst stability, comparing the impact degree of the intensity and duration of climate events on stability over the past 30 a.

2 Materials and methods

2.1 Study area

The research object of this study was Chinese grassland, whose climate is characterized by hydrothermal synchronism. We classified Chinese grassland into six types based on various water and wet conditions found in the 1:1,000,000 Chinese Vegetation Atlas published by the Chinese Academy of Sciences (Editorial Board of Vegetation Map of China, 2007; Huang et al., 2021), including meadow steppe (which accounts for 4.5% of the total area of grassland in China), typical steppe (which accounts for 19.5%), desert steppe (which accounts for 9.4%), alpine steppe (which accounts for 25.0%), temperate meadow (which accounts for 14.8%), and alpine meadow (which accounts for 26.8%). Alpine steppe and alpine meadow are collectively referred to as alpine area grasslands, which are mainly distributed in Xizang Autonomous Region, Qinghai Province, and Gansu Province, and are unique grassland types in China (Fig. 1). Meadow steppe, typical steppe, desert steppe, and temperate meadow are collectively referred to as temperate area grasslands, which are mainly distributed in Inner Mongolia Autonomous Region, Heilongjiang Province, Xinjiang Uygur Autonomous Region, and Qinghai Province, and are the main grassland types in China. These data were derived from the Resources and Environmental Science Data Center of Chinese Academy of Sciences (https://www.resdc.cn/), with a resolution of 1 km, which have higher classification accuracy than International Geosphere-Biosphere Programme (IGBP) classification data (Liu et al., 2022).

2.2 Data

SPEI is a drought index based on precipitation and potential evapotranspiration (PET), which combines the sensitivity of Palmer Drought Severity Index (PDSI) to changes in evaporative demand and the multi-scale characteristics of Standardized Precipitation Index (SPI), (Vicente-Serrano et al., 2010; Beguería et al., 2014). We used SPEI to identify specific climate event year (this study divided climate events on an annual basis) (Isbell et al., 2015; Li et al., 2020b; Hossain et al., 2022). SPEI data were derived from the National Earth System Science Data Center of National Science & Technology Infrastructure (http://www.geodata.cn), which used Global Land Data Assimilation System (GLDAS) data as input. We combined GLDAS data and Penman-Monteith Equation to calculate PET, and then combined Penman-Monteith Equation with precipitation data to calculate SPEI. The synthesized SPEI data has a resolution of 0.25°. We downloaded SPEI monthly interval data from 1990 to 2019 and the resolution has been reduced to 5 km. SPEI-12 data show the dry or wet condition of grassland during the growing season.

One key metric for measuring vegetation growth and nutritional condition is NDVI. We used NDVI to characterize the grassland health status in this study (Hossain et al., 2022). NDVI data used by this study were derived from Earth Engine Data Catalog (https://developers.google.com/earth-engine/datasets/catalog/NOAA_CDR_AVHRR NDVI V5); and we utilized RStudio (Public Benefit Corporation, Boston, Massachusetts, the USA) to call the Google Earth Engine server for monthly synthesis, the resolution was 5 km, and the extraction period was 1990–2019.

The key to calculating grassland ecosystem resistance and resilience lies in the vegetation growth data, specifically NDVI. Therefore, we converted these aforementioned data into a format compatible with software such as MATLAB (Mathworks, Boston, Massachusetts, USA) and then used ArcGIS (Environmental Systems Research Institute, Redlands, California, USA) with bilinear interpolation for resampling to unify the resolution with the original NDVI data at 5 km resolution for further analysis.

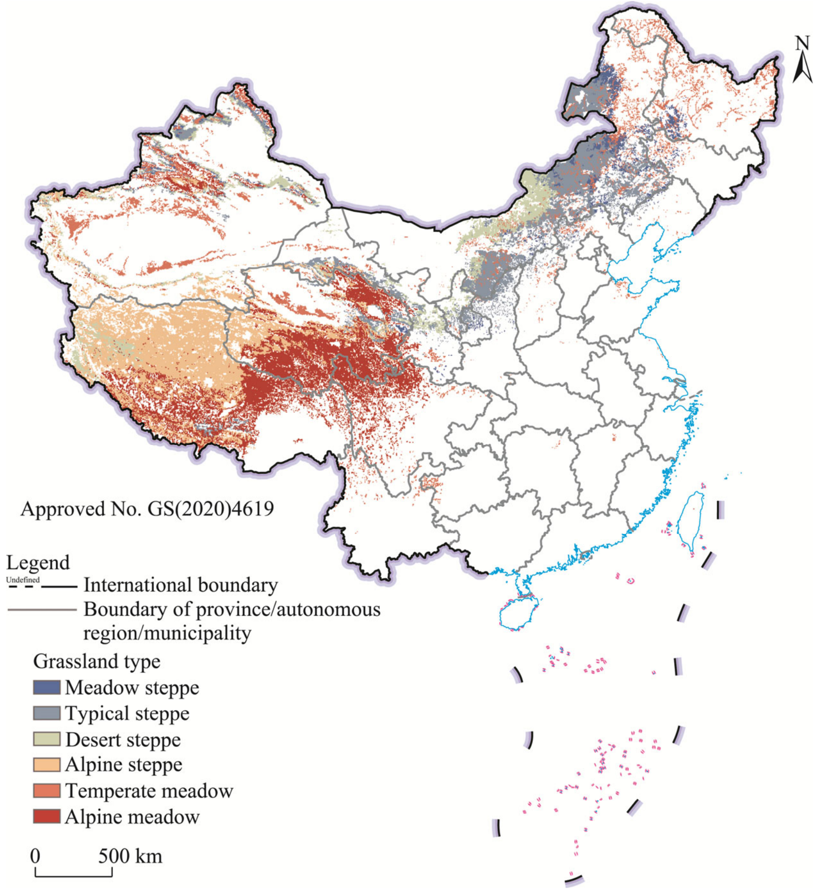

Fig. 1 Distribution of six grassland types in China. Note that this map is based on the standard map (No. GS (2020)4619) of the Map Service System (http://bzdt.ch.mnr.gov.cn/) marked by the Ministry of Natural Resources of the People's Republic of China, and the base map has not been modified.

2.3 Methods

2.3.1 Identification of climate event years

To indicate the intensity and orientation of climate events, this study categorized climate events on an annual basis, which is referred to as "climate event year", and the year started one month after the end of grassland growing season and continued until the end of the next year's growing season month. We categorized SPEI-12 values into five groups including severe wet, mild to moderate wet, normal, mild to moderate drought, and severe drought (Table 1). This study focused solely on the impact of drought and wet climate events on grasslands, thus normal years were only categorized without analysis. To be specific, this study was conducted at an interannual scale; and for each grid cell, when the annual average SPEI-12 value fell within different categorized intervals of various orientations, we defined that grid cell as experiencing severe drought, mild to moderate drought, normal, mild to moderate wet, or severe wet event years (Isbell et al., 2015; Huang and Xia, 2019). The duration of drought and wet events was measured

on a monthly basis. When SPEI-12 value was less than or more than a certain value for three consecutive months (Schwalm et al., 2017), it was defined as a climate event in that year. According to the above method, we calculated the climate event types of each year in the study area from 1990 to 2019 and certain climate event duration of each year.

Table 1 Category of climate event types of grassland ecosystem based on Standardized Precipitation Evapotranspiration Index-12 (SPEI-12) value

Climate event type	SPEI-12	Climate event type	SPEI-12
Severe drought	< –1.28	Mild to moderate wet	0.67–1.28
Mild to moderate drought	–1.28– –0.67	Severe wet	≥1.28
Normal	–0.67–0.67		

In order to observe the spatio-temporal changes in climate events in different grassland types over the past 30 a, we quantified the proportion of drought or wet exposure events on different grassland types and compared climate event durations of each year in different grassland types.

2.3.2 Quantification of vegetation stability

We used resistance and resilience to measure grassland stability under the influence of climate events. Resistance refers to the ability of an ecosystem to maintain a normal growth level when resisting climate events (Li et al., 2020a); resilience refers to the rate at which an ecosystem recovers to its normal growth level after encountering climate event disturbances (Liu et al., 2021). That is to say, if climate events can reduce or increase vegetation growth levels, the higher the rate at which biomass returns to a normal growth level during the recovery period, the stronger the resilience until the speed is fast enough to restore a normal growth level in the following year. For example, the stronger resistance and resilience of vegetation ecosystems after disturbances from climate events indicate that the ecosystems are more stable. The specific calculation method is as follows (Isbell et al., 2015; Huang and Xia, 2019):

Resistance:

$$\Omega = \frac{\overline{Y_n}}{\left|Y_e - \overline{Y_n}\right|}, \tag{1}$$

and resilience:

$$\Delta = \left|\frac{Y_e - \overline{Y_n}}{Y_{e+1} - \overline{Y_n}}\right|, \tag{2}$$

where Ω is the resistance value; Δ is the resilience value; $\overline{Y_n}$ is the normal growth level of an ecosystem in normal years; Y_e is the vegetation growth level in years experiencing climate events; and Y_{e+1} is the vegetation growth level in a normal year after experiencing a climate event in the previous year. Ω and Δ gauge the magnitude of fluctuations in the vegetation growth level in climate event years and recovery years compared with normal years. Smaller fluctuations indicate greater stability, while larger Ω and Δ values correspond to more favorable outcomes. The calculations above are based on the identification of climate types and intensities for climate event years, and they are conducted on a grid-by-grid basis. These formulas indicate that (1) since the calculated values for resistance and resilience are dimensionless, they can be compared across vegetation productivity across different categories and research areas; and (2) the results are symmetrical, which can express grassland type responses to climate events in different orientations (Isbell et al., 2015).

2.3.3 Regression analysis

In order to explore the impact of climate events on grassland stability, we extracted the grids of identified climate event years and eliminated outliers. Using different climate event durations and

intensities as explanatory factors and grassland stability indicators as response variables, we constructed a multiple regression model. The regression coefficients for each explanatory factor were calculated. Building upon the traditional regression model, we employed a standardization method to obtain average parameter estimates for model factors. This yielded standardized regression coefficients along with their corresponding 95% confidence intervals and the relative importance of each influencing factor, expressed as a percentage to explain the degree of impact (Sirami et al., 2019). The relative influence of factors and their interactions can be straightforwardly calculated as the ratio between the parameter estimates of influencing factors, represented in percentages.

In the process of model building, firstly, raw data were preprocessed. Due to the positive skew in the distribution of resistance and resilience indicators, according to the kernel density distribution map, the larger and smaller values less than and greater than 5.0% were removed, respectively (Yoo et al., 2013). For explanatory factors, we set the standardized mean to 0 and the standard deviation (SD) to 1. The influence of explanatory factor on the response variable was that when the explanatory factor changed by one SD unit, the corresponding response variable changed the corresponding value. This method eliminated dimensions, and the regression coefficients for different explanatory factors were directly comparable. Secondly, we used the vif function of RStudio to rule out the multicollinearity problem among the explanatory factors. When the variance inflation factor (VIF) is greater than 10, it is considered that a strong multicollinearity problem exists among the explanatory factors (Lavery et al., 2019). Then, we used the Performance Analytics package of RStudio to explore the distribution, scatter plots, and correlation coefficients among these explanatory factors. Diagnostic tools were run to validate residuals, and the results were ultimately obtained and visualized. All analyses were conducted using RStudio software.

While considering the non-uniformity of units and magnitudes among factors, this method allows for a direct comparison of the obtained coefficients. It effectively addresses issues such as overfitting in random forest models (Scornet, 2016).

3 Results

3.1 Identification of climate events

3.1.1 Identification of climate event years

This study counted the proportions of different climate events in six Chinese grassland types for 30 consecutive years from 1990 to 2019, the proportion means the ratio of the number of grassland grids affected by climate events in that year to the total grid number of that grassland type. The proportion results reflected the climate event annual exposure situation throughout the whole study period (Fig. 2). The exposure of different grassland types to climatic conditions varied significantly from 1990 to 2019. Meadow steppe, typical steppe, desert steppe, and temperate meadow experienced more extensive disruptions due to drought events from 2006 to 2009. Notably, meadow steppe and typical steppe were primarily impacted by drought events, aligning with the findings of Liu et al. (2021) that studied the major drought events in the grassland of Inner Mongolia Autonomous Region in 2008 and 2009. Alpine steppe covered a relatively large area affected by severe wet events in 1990, accounting for over 40.0% of all the alpine steppe area. Alpine meadow encountered significant disruptions due to substantial wet events during 2017–2019, accounting for more than 70.0% of all the alpine meadow area in 2019, predominantly characterized by wet climate conditions. Upon comparing these findings with the grassland type map (Fig. 1), it became apparent that grassland types with a higher susceptibility to drought events were primarily situated in the northwestern and northeastern regions of China. In contrast, those more exposed to wet years were mainly located in the southwestern region. It showed an overall pattern of "more drought events in the north and more wet events in the south".

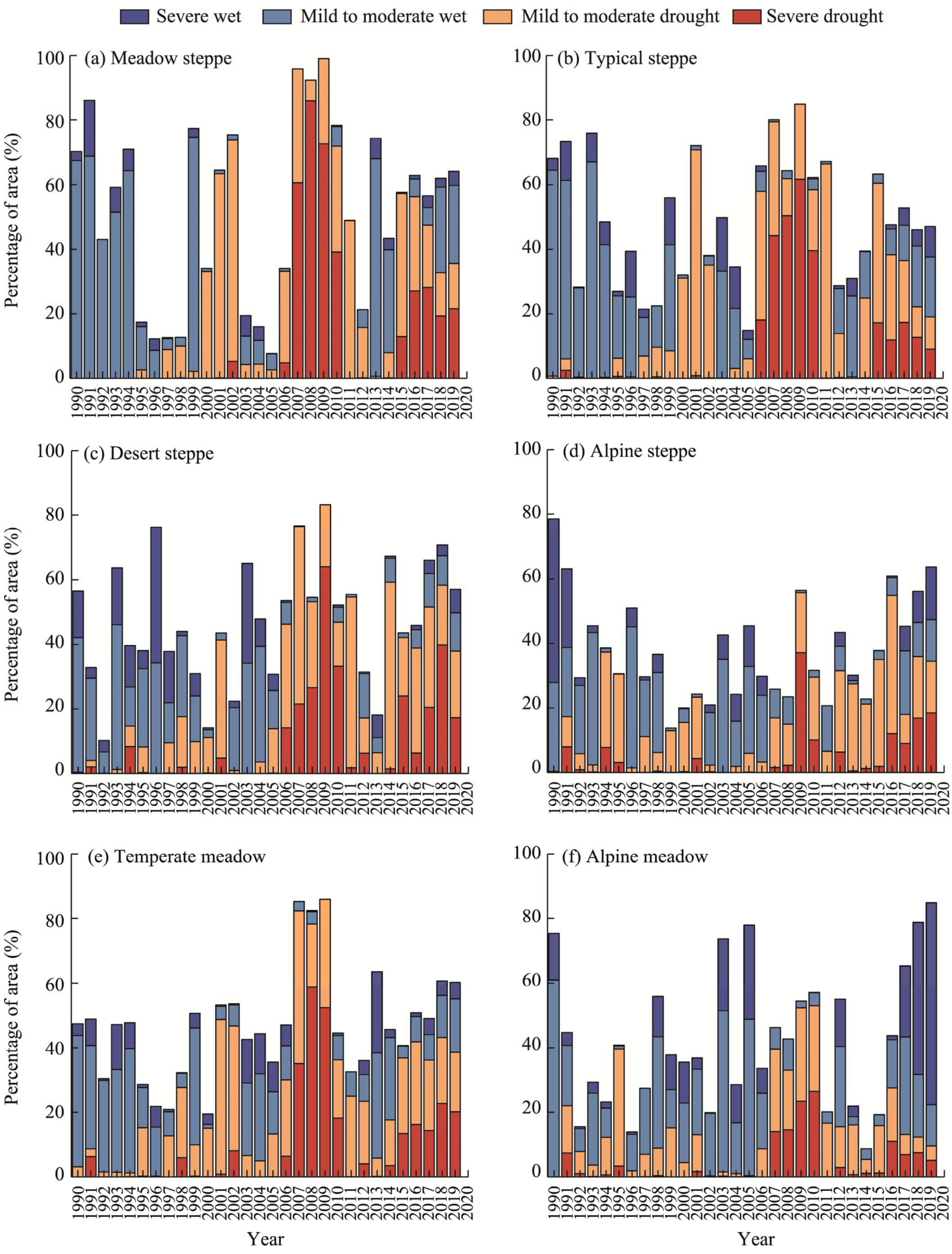

Fig. 2 Percentage of area influenced by different climate event types in six grassland types in China from 1990 to 2019. (a), meadow steppe; (b), typical steppe; (c), desert steppe; (d), alpine steppe; (e), temperate meadow; (f), alpine meadow.

3.1.2 Duration of climate events

Using the aforementioned methodology, this study computed the annual duration of drought events for the six grassland types throughout the study period (Fig. 3). The duration of drought events for the six grassland types varied between 4 and 12 months, and they all exhibited a discernible upward trend over time. Notably, meadow steppe, typical steppe, and temperate meadow displayed more pronounced upward trends. Interestingly, all grassland types except

alpine meadow reached their maximum drought event duration in 2008 or 2009. Among these, meadow steppe endured the longest drought period, spanning more than 11 months.

The duration of wet events for the six grassland types varied from 5 to 10 months, and all exhibited a fluctuating upward trend over time, with the upward trend being generally balanced (Fig. 4). Among them, alpine steppe showed the least noticeable upward trend. The global maximum for alpine steppe occurred in 1995, lasting for more than 11 months.

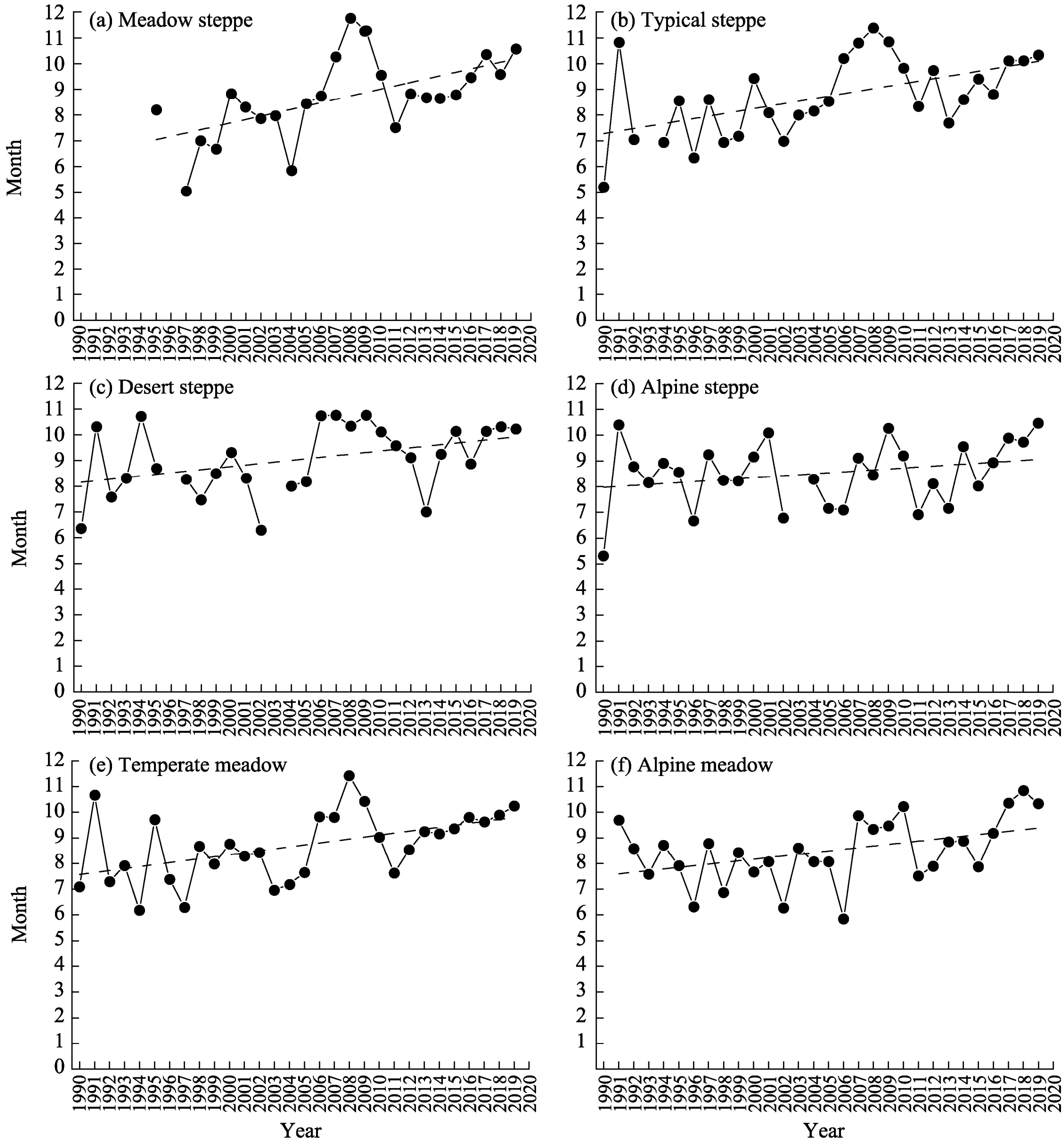

Fig. 3 Annual duration of drought events in six grassland types in China from 1990 to 2019. (a), meadow steppe; (b), typical steppe; (c), desert steppe; (d), alpine steppe; (e), temperate meadow; (f), alpine meadow. The dotted line indicates the trend of annual duration as the number of years increase. The missing data points in the graph indicate that no climate events were detected in that particular year.

3.2 Stability under the influence of climate events

The ability of vegetation to resist drought and wet events showed large spatial differences (Fig. 5a). The resistance values in the northwest and northeast of China were higher (50–55) than other areas. The Qinghai-Tibet Plateau, which is located in the southwest of China, had a lower

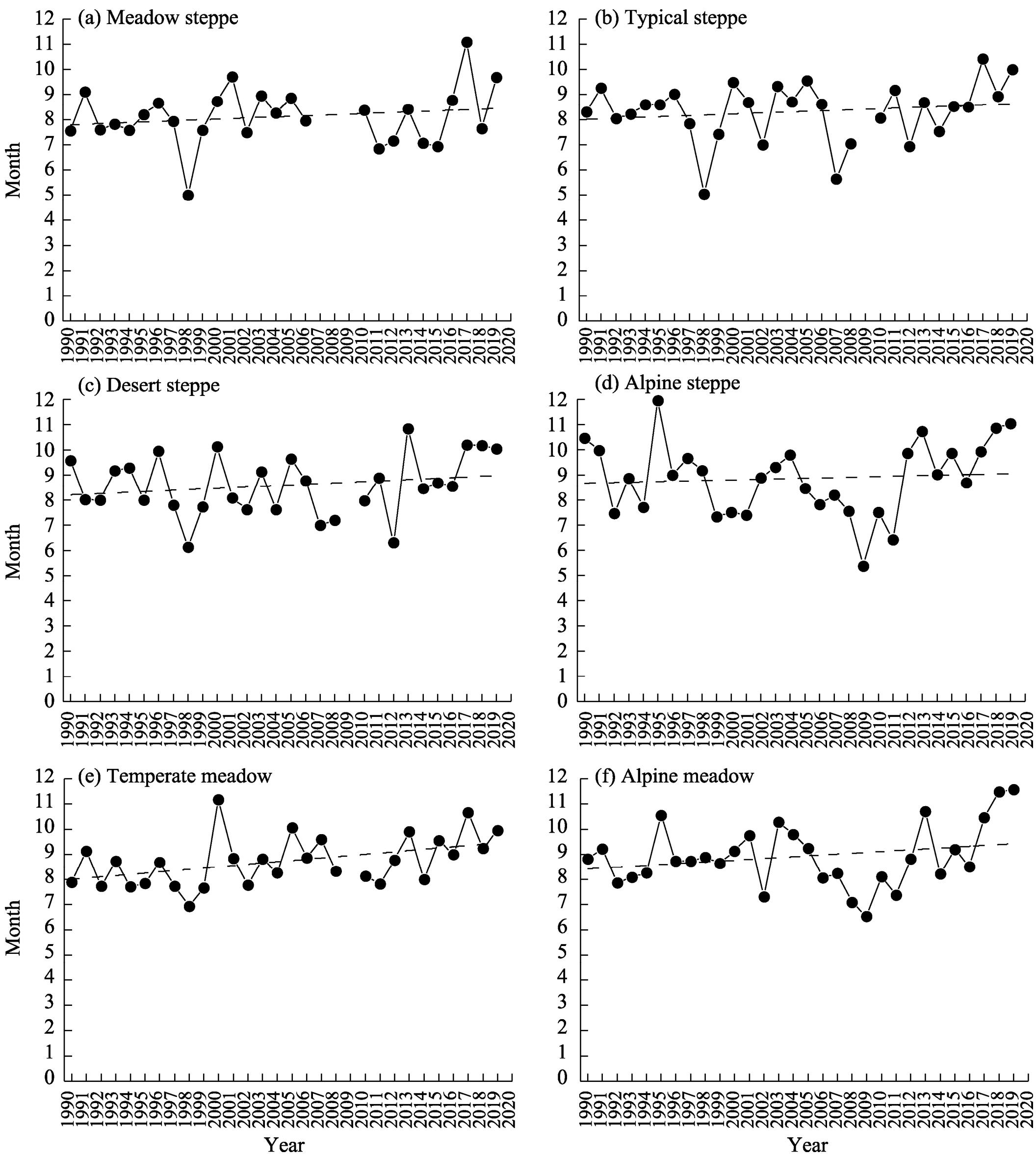

Fig. 4 Annual duration of wet events in six grassland types in China from 1990 to 2019. (a), meadow steppe; (b), typical steppe; (c), desert steppe; (d), alpine steppe; (e), temperate meadow; (f), alpine meadow. The dotted line indicates the trend of annual duration as the number of years increase. The missing data points in the graph indicate that no climate events were detected in that particular year.

resistance value of less than 50. The spatial recovery rate of vegetation to normal levels under the disturbances of drought and wet climate events also exhibited significant variations (Fig. 5b). The central part of Inner Mongolia Autonomous Region in the northeast of China displayed stronger resilience, with the majority of resilience value falling 2–3. Some small areas even showed resilience value exceeding 3. In contrast, the eastern part of the Qinghai-Tibet Plateau in the southwest of China exhibited weaker resilience, with the majority of resilience value ranging 1–2. This region was predominantly characterized by alpine meadows. Divided by the latitude line of the northern edge of the Qinghai-Tibet Plateau, the overall resistance and resilience showed a pattern of high in the north and low in the south. Grassland stability also showed a spatial pattern of high in the north and low in the south.

This study also studied the relationship between the resistance and resilience of different

grassland types (Fig. 6). There were large differences in the resistance and resilience of each grassland type after disturbances from drought and wet climate events (Fig. 6). Compared with other grassland types, meadow steppe exhibited the strongest resistance and resilience. Typical steppe ranked fourth in resistance among the six grassland types and second in resilience. Temperate meadow and alpine meadow ranked second and third, respectively, in resistance, but ranked third-to-last and second-to-last in resilience, respectively. Desert steppe had the poorest resistance and average resilience. Alpine steppe ranked second-to-last in resistance and exhibited the poorest resilience. The rate at which grassland vegetation ecosystems recover to normal growth levels after encountering climate events is particularly noteworthy. In an overall assessment of grassland stability levels, meadow steppe exhibited the highest comprehensive

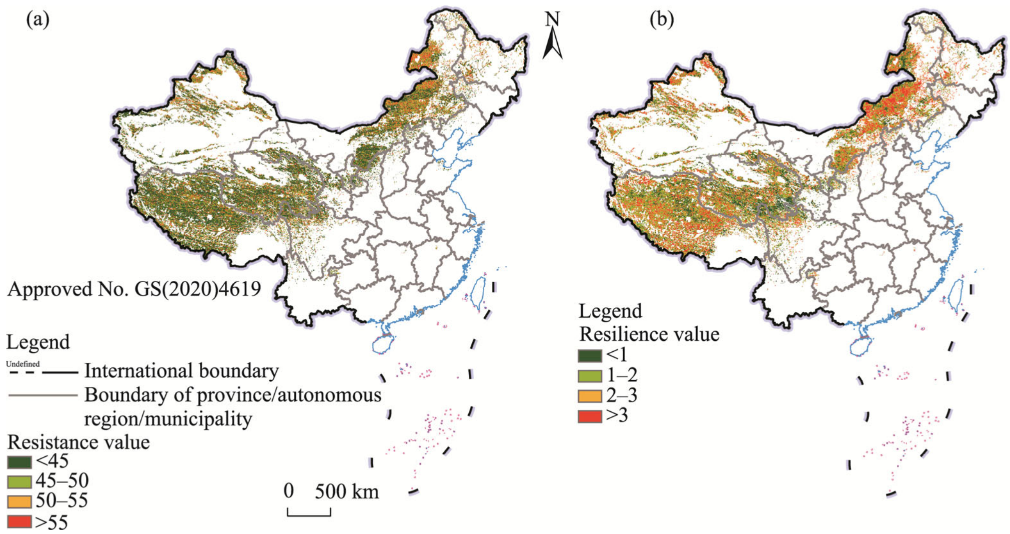

Fig. 5 Distribution of resistance value (a) and resilience value (b) of grassland in China from 1990 to 2019. Note that these maps are based on the standard map (No. GS(2020)4619) of the Map Service System (http://bzdt.ch.mnr.gov.cn/) marked by the Ministry of Natural Resources of the People's Republic of China, and the base map has not been modified.

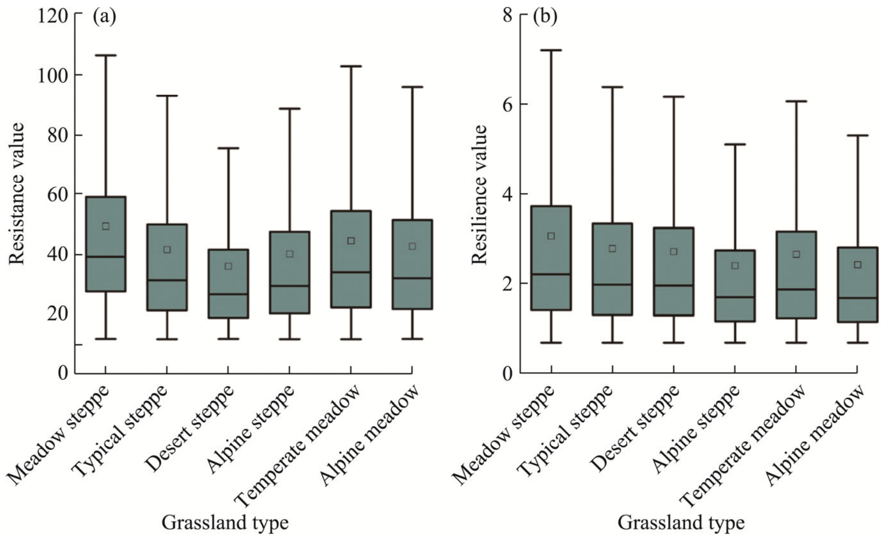

Fig. 6 Resistance value (a) and resilience value (b) of six different grassland types in China from 1990 to 2019. The lines across the boxes indicate the median values, and the points represent the mean values. The lower and upper boxes show the interquartile range (the 25th and 75th percentiles, respectively). The whiskers (the lines on the ends of the boxes) in a box plot correspond to the range within 1.5 times the interquartile range.

stability. Temperate meadow, typical steppe, and alpine meadow fell in an intermediate stability range. Desert steppe and alpine steppe had the poorest comprehensive stability and required more attention.

Furthermore, this study analyzed and compared the resistance and resilience of six grassland types under four climate intensities (i.e., severe drought, mild to moderate drought, mild to moderate wet, and severe wet). Vegetation resistance showed obvious differences under different climate event intensities (Fig. 7). For meadow steppe, which exhibited the highest stability, both its resistance and resilience were strongest under disturbances from climate events other than severe wet and severe drought conditions. Alpine meadow ranked low in resistance and resilience under the influence of drought events, and it had the strongest resistance but the worst resilience under severe wet conditions. In mild to moderate drought and wet conditions, temperate meadow ranked second in both resistance and resilience among the six types of grassland. However, under severe drought and wet conditions, its resistance ranked higher than its resilience. Typical steppe showed intermediate ranking level of resistance but the strongest resilience under severe drought and wet conditions. For desert steppe and alpine steppe, which require the most attention, they exhibited aver resilience under wet climate conditions, ranking third and fourth, respectively, in terms of resilience among the six types of grasslands. However, their resistance under wet climate conditions was weaker than other grassland types, indicating susceptibility to disturbances from wet events with less-than-ideal recovery outcomes. Desert steppe showed the weakest resistance under mild to moderate drought, while alpine steppe showed the weakest resistance and resilience under severe drought, signifying the most significant impact of drought events on stability.

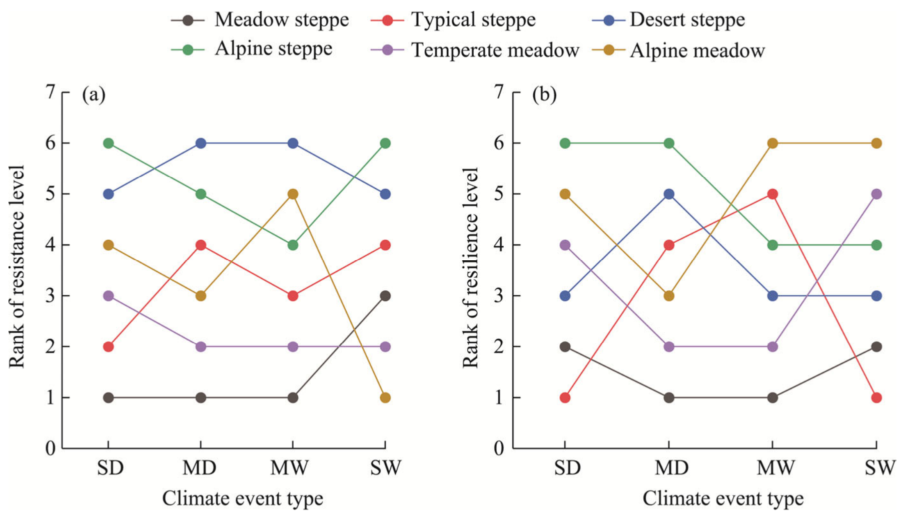

Fig. 7 Rank of resistance (a) and resilience (b) levels of six grassland types under different climate event types in China. SD, severe drought; MD, mild to moderate drought; MW, mild to moderate wet; SW, severe wet.

At the same time, when the intensity of climate events in the drought direction increased, the resistance and resilience of typical steppe, desert steppe, temperate meadow, and alpine meadow showed a coordinated trend. In contrast, when the intensity of climate events in the wet direction increased, the resistance and resilience of typical steppe showed a trade-off, but meadow steppe showed a coordinated trend.

3.3 Impact of climate event duration and intensity on stability

The above results indicated that desert steppe and alpine steppe grassland types had the lowest stability and required attention. In this study, a regression model using standardization was employed to investigate the impact of climate event duration and intensity on these two grassland types. The VIF values obtained using the RStudio for climate event duration and intensity were both less than 10. Standardized climate event duration and intensity factors were then input into

the model, and the following results were obtained (Fig. 8). The model was subjected to a *t*-test, and most grassland types results showed $P<0.001$ for resistance and resilience, indicating a significant relationship between variables (Table S1).

The results indicated that the duration and intensity of different climate event types had varying effects on these two grassland types. In the case of the desert steppe, climate event intensity had a greater impact on its resistance (75.1%) than climate event duration in drought conditions. In comparison, climate event intensity had a greater impact on its resilience (66.3%) than climate event duration in wet conditions. During drought, the resilience of desert steppe was primarily influenced by climate event duration (98.9%) rather than intensity. On the other hand, alpine steppe was mainly influenced by climate event intensity in wet conditions both for resistance (97.8%) and resilience (53.7%) rather than duration.

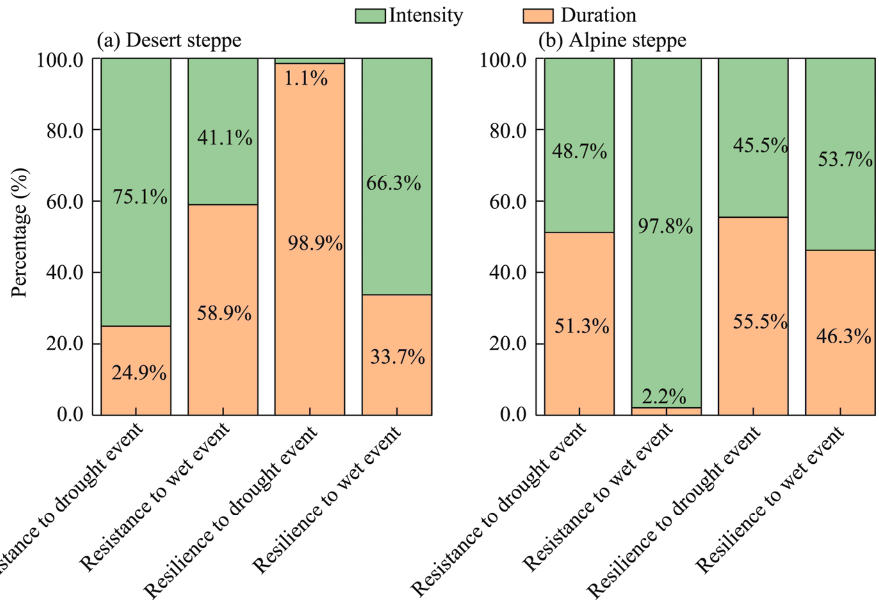

Fig. 8 Effect of the duration and intensity of drought and wet climate events on desert steppe (a) and alpine steppe (b)

4 Discussion

4.1 Differences in stability

As the results, meadow steppe had good stability against drought and wet climate events. It is characterized by a semi-humid climate with moderate rainfall, providing suitable conditions for vegetation growth. As Si et al. (2023) said, meadow steppe exhibits favorable physiological and growth characteristics. In addition, a good environment makes it rich in biodiversity, and the ecosystem structure is more complete. Previous research showed that rich biodiversity can effectively improve the resistance stability of an ecosystem (Isbell et al., 2015). These are the main reasons for the strong overall stability of meadow steppe against climate event disturbances. In terms of different climate types, meadow steppe exhibited remarkable resistance to drought and mild to moderate wet. However, its resistance was generally lower under the disturbance of severe wet, indicating that excessive moisture can inhibit nutrient transport and reduce biodiversity and biomass (Zhou et al., 2023). This, in turn, slows the recovery rate and disrupts the stability of meadow steppe. Currently, there are few studies on the damage and harm caused by wet climates to grassland, and this can be further explored in future studies. Compared to other grassland types, meadow steppe exhibited stronger resilience after drought and wet disturbances, possibly attributed to lower productivity observed during periodic drought events caused by hydraulic

depletion and carbon starvation. However, it may recover more rapidly due to resource availability under normal climatic conditions (Zhang et al., 2019). Following droughts, precipitation, along with sufficient moisture and effective photosynthesis, provides conditions for its growth state recovery.

Desert steppe and alpine steppe vegetation ecosystems had the worst stability under the influence of climate events. Desert steppe is a grassland type that transforms from grassland to desert. It has poor soil condition and a harsh environment. The community species in this growth environment have a single simple structure and less biodiversity (Zhang et al., 2023). The vegetation coverage of desert steppe and alpine steppe was low (Fig. S1). Wang et al. (2023) thought that a certain vegetation type along with lower coverage has lower recovery stability in response to disturbance events. The non-uniform increase in ground temperature caused by global climate warming also reduces their temporal stability during the alpine steppe growing season (Han et al., 2023). In addition, affected by human activities, unreasonable grazing, reclamation, and mineral mining have directly led to grassland desertification. The above factors are the main reasons for the low stability of desert steppe and alpine steppe. Grassland ecosystems respond to changes in precipitation. The Qinghai-Tibet Plateau is becoming increasingly humid, and the high mountain meadow in the northern region of Qinghai-Tibet Plateau is significantly increased in NDVI because of increased precipitation, which may lead to an increase in the stability of grassland's resilience in the future (Fu et al., 2018). The increase in low-level precipitation contributes to an increase in the species diversity of grassland in the northern part of Qinghai-Tibet Plateau, thereby increasing the resistance of grassland (Xiao et al., 2023). The results obtained by this study were similar to those of Huang et al. (2021) the rank of resistance and resilience levels of different grassland types is similar. The differences between the results got by this study and previous research may be due to the differences in study period, drought threshold classification method, and SPEI data source. The wet and drought threshold classification used in this study was proposed by Isbell et al. (2015). It refers to the SPEI-12 value obtained from more than 4000 sites worldwide over the past century and is divided by percentile thresholds, thus having more unified and representative. In addition, the SPEI-12 value used in this study was calculated using the Penman-Monteith Equation. Given the rich data sources, the Penman-Monteith Equation is universal and accurate.

The standardized regression model used in this study has been widely used in the fields of ecology and botany. Gross et al. (2017) used this method to study the relationship between multiple biological traits and biodiversity. Grilli et al. (2017) and García-Palacios et al. (2018) also studied the impact of biodiversity on plant stability under extreme climate backgrounds. This method is simple and easy to implement. It adds the concepts of standardization and variance decomposition to the traditional regression model, allowing the research object to maintain independence, and the results obtained can more intuitively reflect the independent effects of each factor. This study investigated the impact of the intensity and duration of climate events on the stability of grassland ecosystem and clearly provided the percentage of whether the duration or intensity of climate events causes differences in vegetation ecosystem stability between the same grassland types. This study further clarified the differences in response patterns of different grassland types to various climate events in terms of intensity and duration, providing insights and references for grassland ecosystem management.

4.2 Suggestions and limitations

Global climate warming is an indisputable fact, and the increase and intensification of climate events caused by it has become a global trend. In recent years, there has been a trend of coexistence and frequent occurrence of droughts and floods in many regions worldwide (Yang, 2019). Complex climate change has brought great uncertainty to grassland growth, which may lead to varying degrees of degradation. In particular, desert steppe and alpine steppe, which are the least stable, urgently need attention. For these two more vulnerable grassland types, we should put forward the idea of comprehensive management based on their characteristics in responding

to climate events and take a variety of measures to protect them. For example, during the non-growing grassland vegetation season, mechanical methods can be employed to improve soil properties and water use efficiency. This creates favorable conditions for plant growth, enhancing productivity and reducing vulnerability to climate events. During the growing season, it is advisable to reduce excessive grazing and human-induced activities such as cultivation. Additionally, establishing protected areas in key regions can be targeted to mitigate the impacts of human interference. Grassland types that are more sensitive to the duration and intensity of climate events can predict the occurrence of climate events by monitoring climate factors such as precipitation and temperature so that early artificial intervention can help them recover as quickly as possible.

In addition, this article has certain limitations. This study considered the impact of long-term climate events on grassland vegetation in annual units. However, the stability of Chinese grasslands in response to short-term pulse events (such as sudden drought and extreme precipitation) is still unknown, and further research should be conducted in the future. Moreover, regarding the impact of the duration and intensity of climate events on vegetation ecosystem stability in the same grassland type, this study has only provided a comparative analysis of the magnitude of these impacts. In the future, further curve fitting can be conducted to clarify the relationship between them, thus offering more comprehensive recommendations for grassland management.

5 Conclusions

This study mainly analyzed the stability differences in six grassland types in China from 1990 to 2019 when disturbed by drought and wet climate events and used a standardized regression model to explore further differences in the impact of the duration and intensity of climate events on grassland stability. This study found that the resistance and resilience of different grassland types differ significantly. Among them, the resistance and resilience of meadow steppe were at a high level, indicating that meadow steppe had strong stability and was better able to adapt to changes in environmental factors. The resilience and resilience of typical grassland, alpine meadow, and temperate grassland ranked at intermediate levels among the six types of grassland ecosystems. In contrast, among the six types of grassland ecosystems, desert grassland exhibited the lowest resistance, and had no outstanding performance of resilience, while alpine meadow showed the poorest resilience and lacked significant resistance, so their management and protection should be strengthened. Different grassland types exhibited varying responses to climate events of different intensities. Alpine steppe showed the weakest resilience when facing mild to moderate drought and severe drought events. Once subjected to destructive disruptions caused by drought events, the later recovery of alpine steppe may become challenging. Desert steppe had the poorest resistance to both mild to moderate drought and mild to moderate wet environments, but its resilience was better than that of alpine steppe. Regarding the impact of the duration and intensity of climate events on vegetation ecosystem stability of the same grassland type, for desert steppe, during drought events, the recovery was mainly influenced by the duration, with intensity having less apparent effects. On the other hand, for alpine steppe in wet environments, the primary influence was from intensity, while the duration showed less noticeable effects. This study further clarified the mechanisms through which wet and dry climate events affect grassland vegetation stability, laying the groundwork for more in-depth research. The obtained results can provide decisions and solutions for grassland ecosystem governance.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

Conceptualization: CAO Wenyu, BAI Jianjun; Data curation: CAO Wenyu, YU Leshan; Methodology: CAO Wenyu; Writing-original draft preparation: CAO Wenyu; Writing - review and editing: CAO Wenyu, BAI Jianjun; Funding acquisition: BAI Jianjun; Resources: CAO Wenyu, BAI Jianjun; Supervision: BAI Jianjun; Visualization: CAO Wenyu. All authors approved the manuscript.

References

Beguería S, Vicente-Serrano S M, Reig F, et al. 2014. Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. International Journal of Climatology, 34(10): 3001–3023.

Chen J J, Chi Y G, Zhou W, et al. 2021. Quantifying the dimensionalities and drivers of ecosystem stability at global scale. Journal of Geophysical Research-Biogeosciences, 126(4): e2020JG006041, doi: 10.1029/2020JG006041.

Creedy T J, Asare R A, Morel A C, et al. 2022. Climate change alters impacts of extreme climate events on a tropical perennial tree crop. Scientific Reports, 12(1): 19653, doi: 10.1038/s41598-022-22967-7.

de Keersmaecker W, Lhermitte S, Tits L, et al. 2015. A model quantifying global vegetation resistance and resilience to short-term climate anomalies and their relationship with vegetation cover. Global Ecology and Biogeography, 24(5): 539–548.

Easterling D R, Meehl G A, Parmesan C, et al. 2000. Climate extremes: Observations, modeling, and impacts. Science, 289(5487): 2068–2074.

Editorial Board of Vegetation Map of China. 2007. Vegetation Atlas of China (1:1000000). Beijing: Geological Publishing House.

Fan X, Hao X M, Hao H C, et al. 2021. Comprehensive assessment indicator of ecosystem resilience in Central Asia. Water, 13(2): 124, doi: 10.3390/w13020124.

Fu G, Shen Z X, Zhang X Z. 2018. Increased precipitation has stronger effects on plant production of an alpine meadow than does experimental warming in the Northern Tibetan Plateau. Agricultural and Forest Meteorology, 249: 11–21.

García-Palacios P, Gross N, Gaitan J, et al. 2018. Climate mediates the biodiversity-ecosystem stability relationship globally. Proceedings of the National Academy of Sciences of the United States of America, 115(33): 8400–8405.

Grilli J, Barabas G, Michalska-Smith M J, et al. 2017. Higher-order interactions stabilize dynamics in competitive network models. Nature, 548(7666): 210–213.

Gross N, Bagousse-Pinguet Y L, Liancourt P, et al. 2017. Functional trait diversity maximizes ecosystem multifunctionality. Nature Ecology & Evolution, 1(5): 0132, doi: 10.1038/s41559-017-0132.

Han F S, Yu C Q, Fu G. 2023. Non-growing/growing season non-uniform-warming increases precipitation use efficiency but reduces its temporal stability in an alpine meadow. Frontiers in Plant Science, 14: 1090204, doi: 10.3389/fpls.2023.1090204.

Hansen B B, Gamelon M, Albon S D, et al. 2019. More frequent extreme climate events stabilize reindeer population dynamics. Nature Communications, 10: 1616, doi: 10.1038/s41467-019-09332-5.

Hossain M L, Li J F, Hoffmann S, et al. 2022. Biodiversity showed positive effects on resistance but mixed effects on resilience to climatic extremes in a long-term grassland experiment. Science of the Total Environment, 827: 154322, doi: 10.1016/j.scitotenv.2022.154322.

Hu Y Z, Ding R S, Kang S Z, et al. 2022. The trade-offs between resistance and resilience of forage stay robust with varied growth potentials under different soil water and salt stress. Science of the Total Environment, 846: 157421, doi: 10.1016/j.scitotenv.2022.157421.

Huang K, Xia J Y. 2019. High ecosystem stability of evergreen broadleaf forests under severe droughts. Global Change Biology, 25(10): 3494–3503.

Huang W J, Wang W, Cao M, et al. 2021. Local climate and biodiversity affect the stability of China's grasslands in response to drought. Science of the Total Environment, 768: 145482, doi: 10.1016/j.scitotenv.2021.145482.

Isbell F, Craven D, Connolly J, et al. 2015. Biodiversity increases the resistance of ecosystem productivity to climate extremes. Nature, 526(7574): 574–577.

Ives A R, Carpenter S R. 2007. Stability and diversity of ecosystems. Science, 317(5834): 58–62.

Jiao W Z, Wang L X, Wang H L, et al. 2022. Comprehensive quantification of the responses of ecosystem production and respiration to drought time scale, intensity and timing in humid environments: A FLUXNET synthesis. Journal of Geophysical Research-Biogeosciences, 127(5): e2021JG006431, doi: 10.1029/2021JG006431.

King A D, Donat M G, Fischer E M, et al. 2015. The timing of anthropogenic emergence in simulated climate extremes. Environmental Research Letters, 10(9): 094015, doi: 10.1088/1748-9326/10/9/094015.

Lavery M R, Acharya P, Sivo S A, et al. 2019. Number of predictors and multicollinearity: What are their effects on error and bias in regression? Communications in Statistics-Simulation and Computation, 48(1): 27–38.

Li M, Wu J S, He Y T, et al. 2020a. Dimensionality of grassland stability shifts along with altitudes on the Tibetan Plateau. Agricultural and Forest Meteorology, 291: 108080, doi: 10.1016/j.agrformet.2020.108080.

Li X Y, Piao S L, Wang K, et al. 2020b. Temporal trade-off between gymnosperm resistance and resilience increases forest sensitivity to extreme drought. Nature Ecology & Evolution, 4(8): 1075–1083.

Liu Y, Ren H, Hu T, et al. 2022. Spatiotemporal dynamics of NDVI of grassland and its response to multi-scale drought in China. Research of Soil and Water Conservation, 29(1): 153–161. (in Chinese)

Liu Y J, You C H, Zhang Y G, et al. 2021. Resistance and resilience of grasslands to drought detected by SIF in Inner Mongolia, China. Agricultural and Forest Meteorology, 308–309: 108567, doi: 10.1016/j.agrformet.2021.108567.

Schwalm C R, Anderegg W R L, Michalak A M, et al. 2017. Global patterns of drought recovery. Nature, 548(7666): 202–205.

Scornet E. 2016. Random forests and kernel methods. IEEE Transactions on Information Theory, 62(3): 1485–1500.

Si Y F, Li H, Li Z H, et al. 2023. Response of functional traits of key species in meadow steppe to long-term grazing and grazing exclusion. Agricultural Sciences in China, 56(18): 3693–3708. (in Chinese)

Sirami C, Gross N, Baillod A B, et al. 2019. Increasing crop heterogeneity enhances multitrophic diversity across agricultural regions. Proceedings of the National Academy of Sciences of the United States of America, 116(33): 16442–16447.

Stott P. 2016. How climate change affects extreme weather events: Research can increasingly determine the contribution of climate change to extreme events such as droughts. Science, 352(6293): 1517–1518.

van Ruijven J, Berendse F. 2010. Diversity enhances community recovery, but not resistance, after drought. Journal of Ecology, 98(1): 81–86.

Vicente-Serrano S M, Beguería S, Lopez-Moreno J I. 2010. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. Journal of Climate, 23(7): 1696–1718.

Wang Z Z, Fu B J, Wu X T, et al. 2023. Vegetation resilience does not increase consistently with greening in China's Loess Plateau. Communications Earth & Environment, 4(1): 336, doi: 10.1038/s43247-023-01000-3.

Xiao J Y, Yu C Q, Fu G. 2023. Response of aboveground net primary production, species and phylogenetic diversity to warming and increased precipitation in an alpine meadow. Plants, 12(17): 3017, doi: 10.3390/plants12173017.

Xu Z X, di Vittorio A. 2021. Hydrological analysis in watersheds with a variable-resolution global climate model (VR-CESM). Journal of Hydrology, 601: 126646, doi: 10.1016/j.jhydrol.2021.126646.

Yang J W, Chen H, Hou Y K, et al. 2019. A method to identify the drought-flood transition based on the meteorological drought index. Acta Geographica Sinica, 74(11): 2358–2370. (in Chinese)

Yoo S H, Park C H. 2013. MCP, kernel density estimation and LoCoH analysis for the core area zoning of the red-crowned Crane's feeding habitat in Cheorwon, Korea. Korean Journal of Environment and Ecology, 27(1): 11–21. (in Korean)

Yuan Q, Xu Z, Shi W, et al. 2004. Establishment of the sharing information system of grassland resources in China. Grassland of China, 26(4): 16–20. (in Chinese)

Zhang D, Guo Y F, Qi W, et al. 2023. Study on the composition and diversity of plant communities in different degradation succession sequences of the Ordos desert grassland. Inner Mongolia Water Resources, 10: 3–5. (in Chinese)

Zhang F Y, Quan Q, Ma F F, et al. 2019. Differential responses of ecosystem carbon flux components to experimental precipitation gradient in an alpine meadow. Functional Ecology, 33(5): 889–900.

Zhou X, Wang Y, Li J. 2023. Response of plant community composition to precipitation changes in typical grasslands in the Loess Plateau. Biodiversity Science, 31(3): 42–51.

Appendix

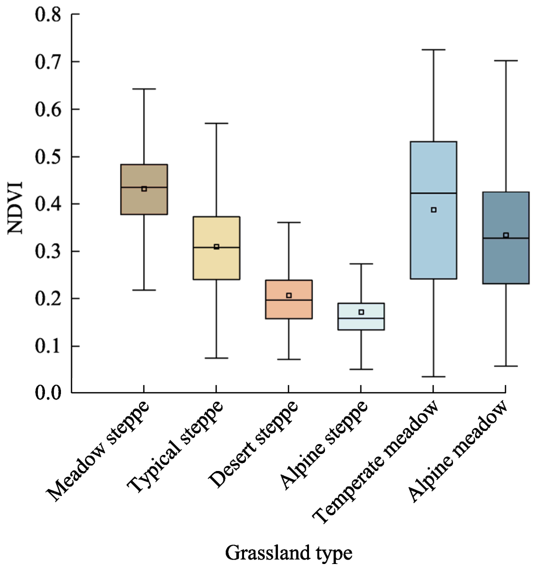

Fig. S1 Box plot of mean Normalized Different Vegetation Index (NDVI) for different grassland types in China from 1990 to 2019. The lines across the boxes indicate the median values, and the points represent the mean values. The lower and upper boxes show the interquartile range (the 25th and 75th percentiles, respectively). The whiskers (the lines on the ends of the boxes) in a box plot correspond to the range within 1.5 times the interquartile range.

Table S1 Results of the response model of the resistance and resilience of desert steppe and alpine steppe to the intensity and duration of climate event under the influence of drought and wet climate event

Grassland type	Capability	Aspect	Estimate	SE	*t*-value	*P* (>|*t*|) value
Desert steppe	Resistance to drought event	Intensity	0.061	0.005	12.578	0.000***
		Duration	–0.020	0.005	–4.204	0.000***
	Resistance to wet event	Intensity	–0.114	0.005	–21.690	0.000***
		Duration	0.164	0.005	31.240	0.000***
	Resilience to drought event	Intensity	–0.001	0.014	–0.104	0.917
		Duration	0.093	0.014	6.559	0.000***
	Resilience to wet event	Intensity	0.167	0.012	13.372	0.000***
		Duration	–0.085	0.012	–6.788	0.000***
Alpine steppe	Resistance to drought event	Intensity	0.101	0.003	29.050	0.000***
		Duration	–0.107	0.003	–30.610	0.000***
	Resistance to wet event	Intensity	–0.059	0.003	17.211	0.000***
		Duration	–0.001	0.003	–0.385	0.700
	Resilience to drought event	Intensity	0.147	0.018	8.146	0.000***
		Duration	–0.183	0.018	–10.164	0.000***
	Resilience to wet event	Intensity	0.182	0.013	13.370	0.000***
		Duration	–0.157	0.013	–11.530	0.000***

Note: SE, standard error; ***, significant at $P<0.001$ level.